# Phase Transitions, Gravitational Waves, and Composite Dark Matter

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(DESY)

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# Outline

- DM from confining SU(N)
- First order Phase Transitions
  - PT dynamics from lattice?
- Gravitational Waves from FOPT
- Detection - Ground, Space, PTA

# Composite DM

- Alternative to elementary WIMP models
- Phenomenologically viable, “generic” possibility in presence of hidden sectors
- Some nice features:
  - DM stability, mass scale
  - Symmetric component annihilation for ADM
  - Self-interactions

# Dark QCD

- Models I'm interested in here
- Nonabelian SU(N) dark sector, confinement scale $\Lambda_d$
- $n_f$ light/massless flavours

$n_f = 0$

Glueball DM

PT from center symmetry restoration

$n_f > 0$

Dark Baryons or Dark Pions

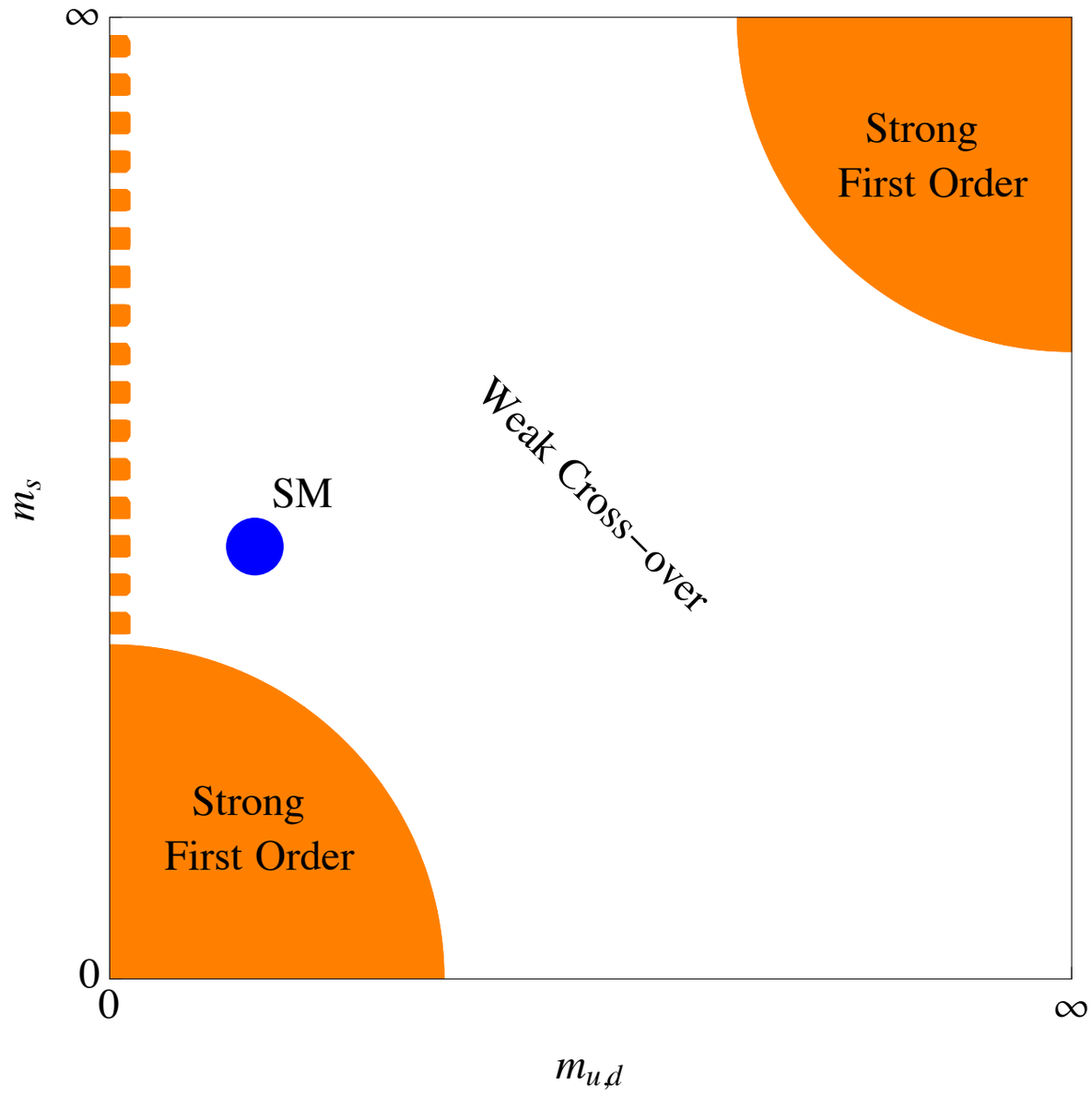
Chiral Symmetry Breaking

# The Dark Phase Transition

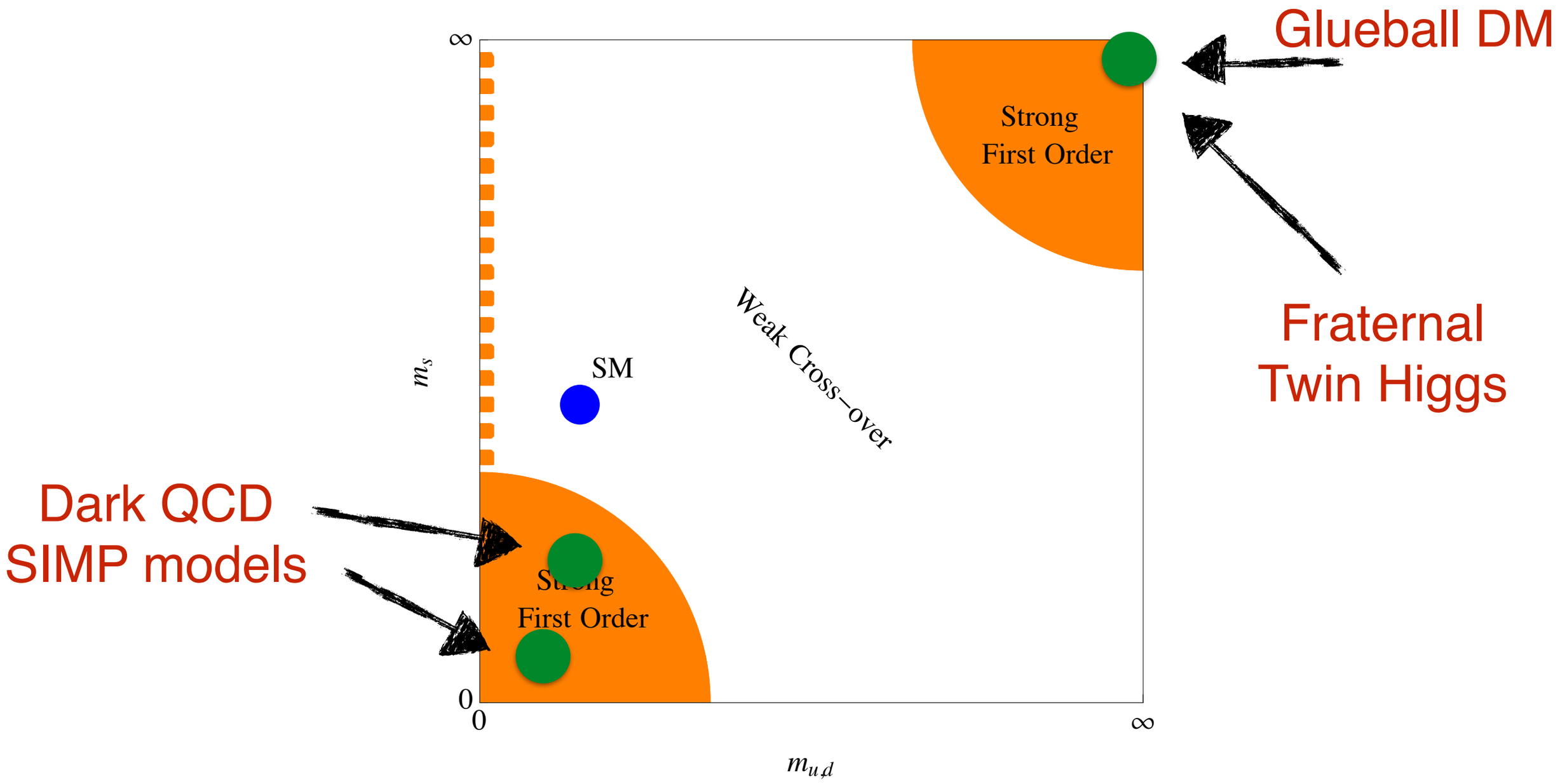
# Phase Transition

- SU(N) dark sectors well motivated
- Confinement/chiral symmetry breaking phase transition at scale $\Lambda_d$
  - DM: $\Lambda_d \sim M_{\rm DM}$ (MeV - 100 TeV)
  - Naturalness: $\Lambda_d \sim \text{few} \times \Lambda_{\rm QCD}$
- First order PT in large class of models
- Still possible if LHC finds no new physics

# QCD Phase Diagram



# Phase Diagram II



# SU(N) - PT

- Consider $SU(N_d)$ with $n_f$ massless flavours
- PT is first order for
  - $N_d \geq 3 \ , \quad n_f = 0$ Svetitsky, Yaffe, 1982 M. Panero, 2009
  - $N_d \geq 3 \ , \quad 3 \leq n_f < 4N_d$ Pisarski, Wilczek, 1983
- Not for:
  - $n_f = 1$ (no global symmetry, no PT)
  - $n_f = 2$ (not yet known)

# SU(N) - PT 2

- One more parameter: $\Theta$ angle
- Effect on PT not well studied

M. Anber, 2013
Garcia-Garcia, Lasenby, March-Russell, 2015

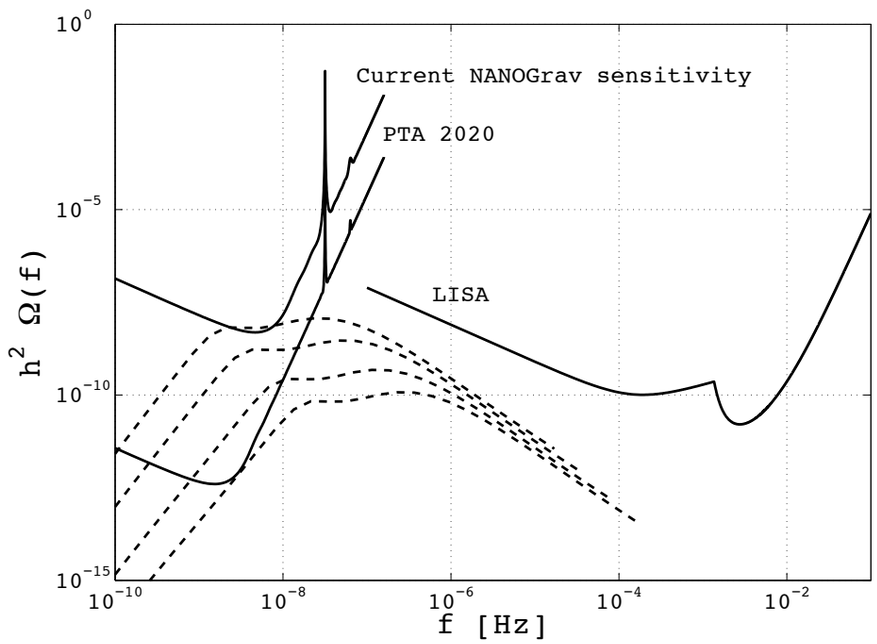
- $N_d,\ n_f$ dependence of PT strength?

Panero, 2009

- Finite density/chemical potentials?
  - QCD FOPT?

    Schwarz, Stuke, 2009
  - GW signal:

    Caprini, Durrer, Siemens, 2009



# Questions for Lattice

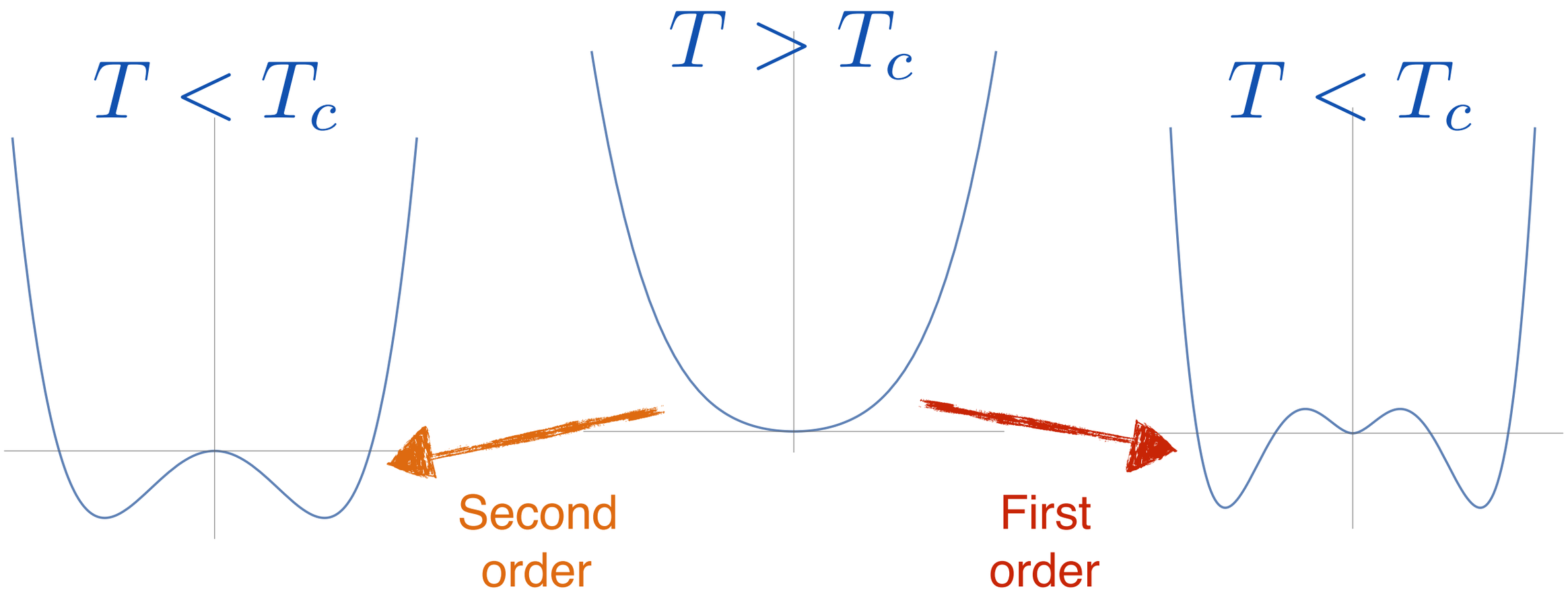
- Dynamics of PT known from lattice?
  - Latent heat
  - Bubble nucleation rate
    - Dependence on $N_d,\ n_f$
    - theta param, chem. potentials?
- At least some of this is known AFAIK
- For Cosmology: $T < T_C$ relevant

I'd be happy to collaborate!

# Gravitational Wave spectra from FOPT

# Cosmological Phase Transitions

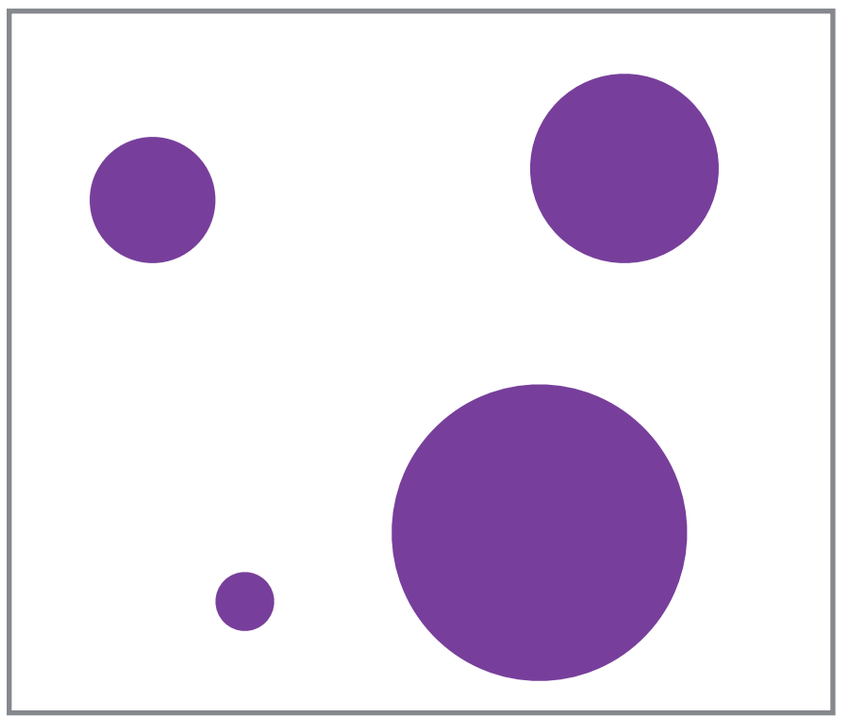
- Early Universe in symmetric phase (e.g. unbroken electroweak symmetry)

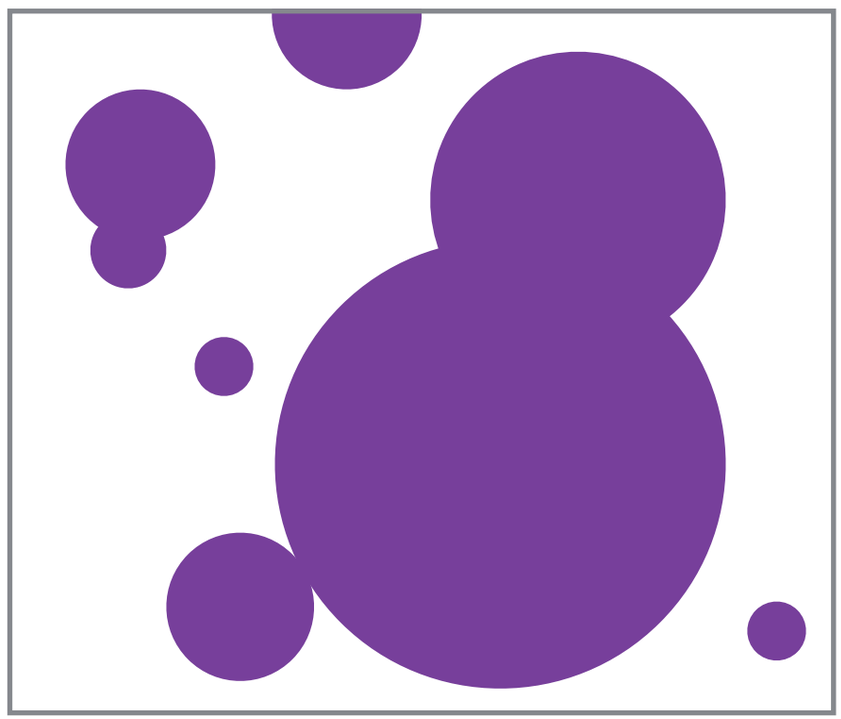


# GWs from PTs

First order PT → Bubbles nucleate, expand

Bubble collisions → Gravitational Waves

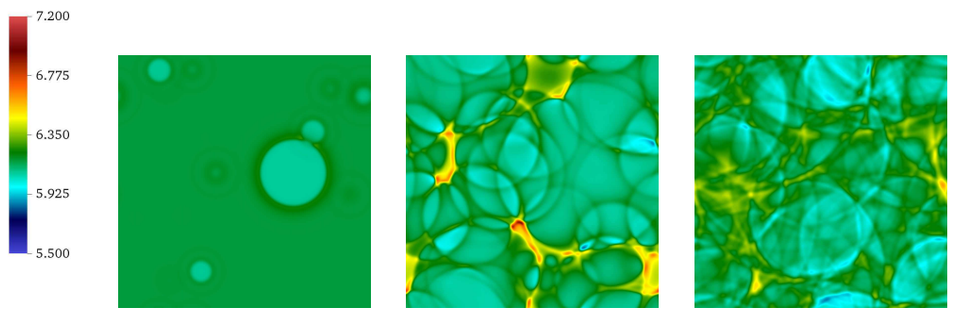




# Signal is Universal

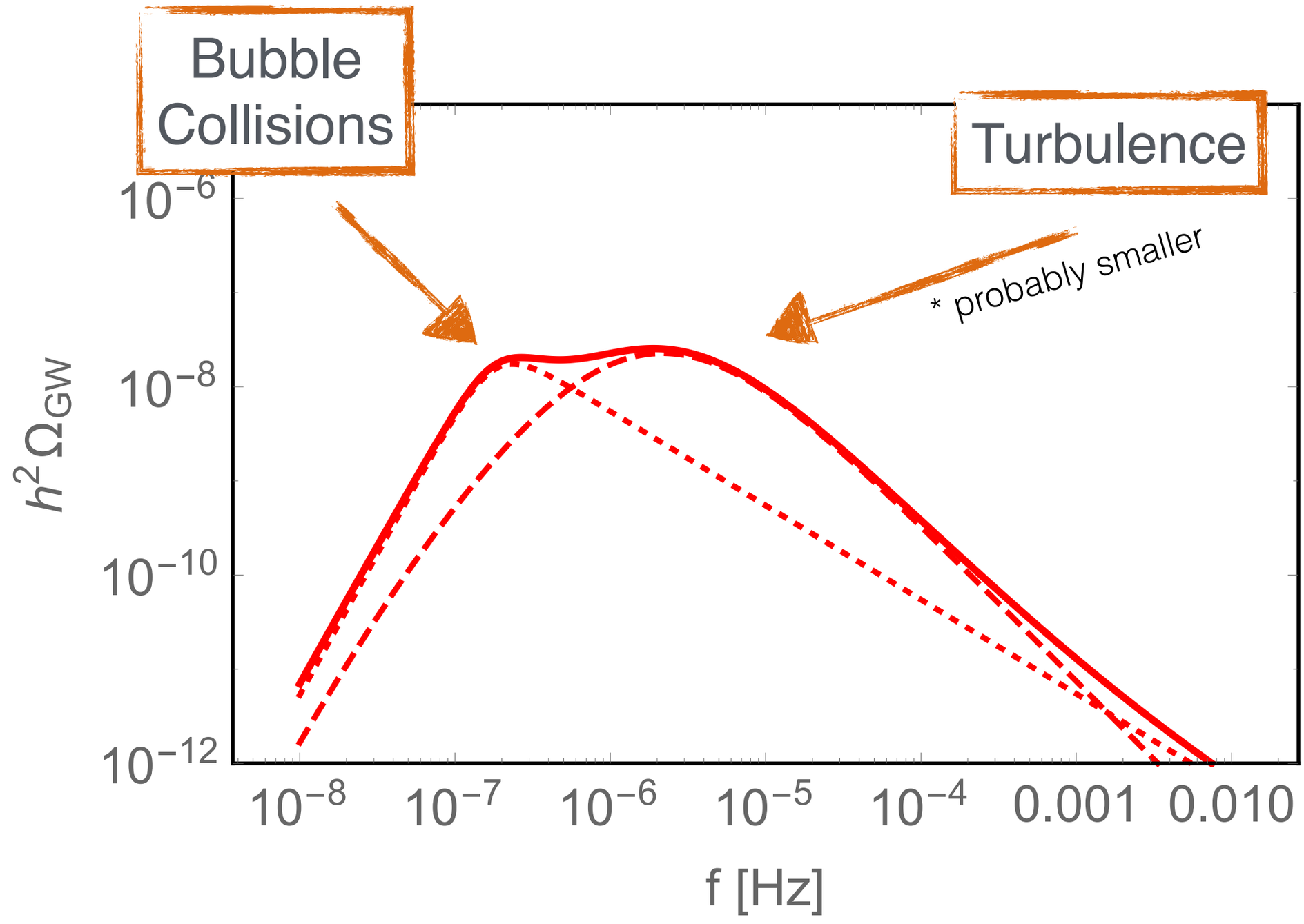
- PT characterised by few parameters:
  - Latent heat $\alpha \approx \frac{\Omega_{\rm vacuum}}{\Omega_{\rm rad}}$
  - Bubble wall velocity $v$
  - Bubble nucleation rate $\beta$
  - PT temperature $T_*$
- Three physical contributions
  - Bubble wall collisions
  - Turbulence
  - Sound waves

Extensive numerical simulations. Recently e.g. Hindmarsh et al:
Sound wave contributions




Phenomenological Parameterisations:
Caprini et al, 1512.06239

# GW signal


Bubble Collisions
Turbulence
* probably smaller
$10^{-6}$
$10^{-8}$
$10^{-10}$
$10^{-12}$
$h^2\Omega_{GW}$
$10^{-8}$
$10^{-7}$
$10^{-6}$
$10^{-5}$
$10^{-4}$
0.001
0.010
f [Hz]

# Peak Frequency

- Redshift:

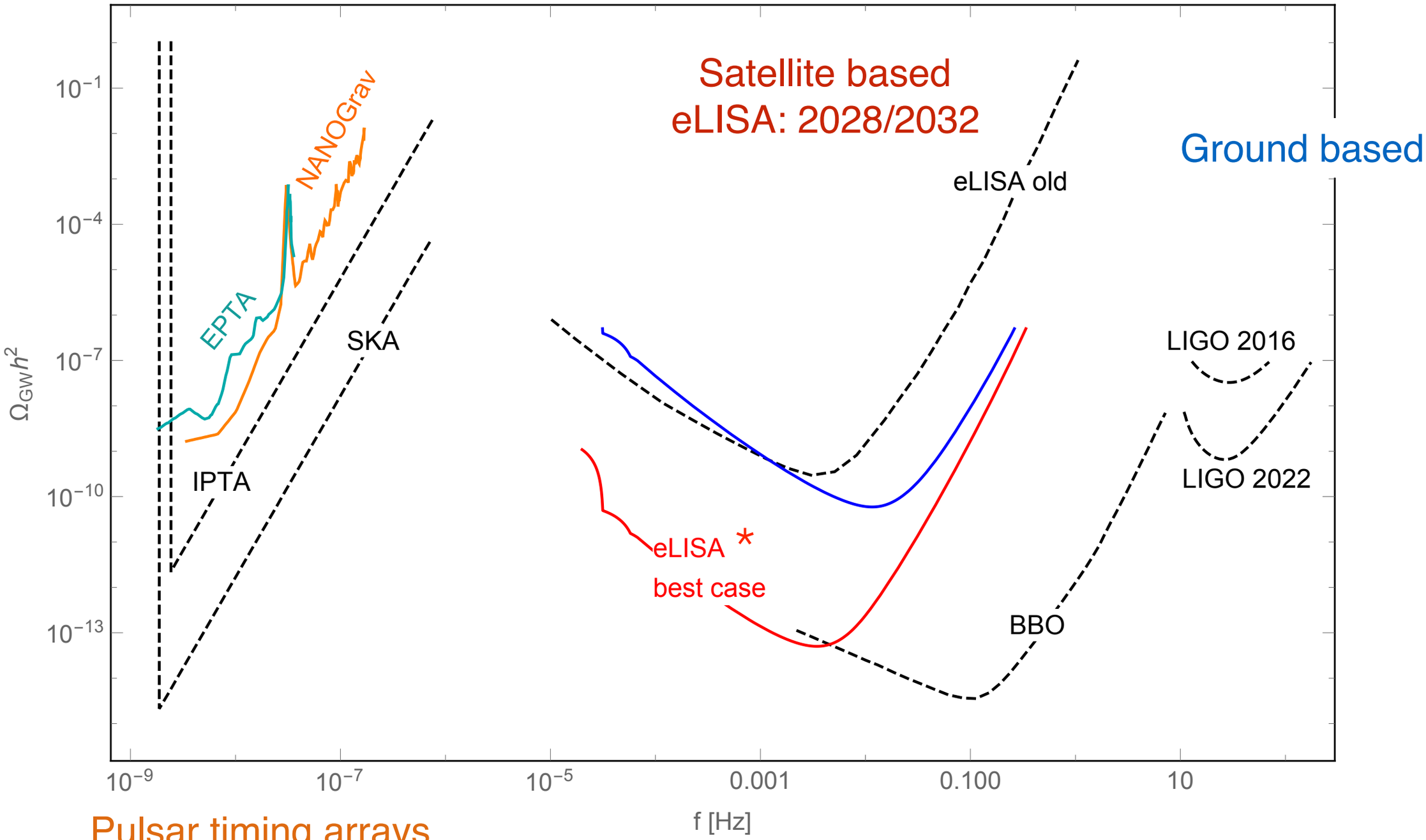
$$f = \frac{a_*}{a_0} H_* \frac{f_*}{H_*} = 1.59 \times 10^{-7}\ \mathrm{Hz} \times \left(\frac{g_*}{80}\right)^{\frac{1}{6}} \times \left(\frac{T_*}{1\ \mathrm{GeV}}\right) \times \frac{f_*}{H_*}$$

- Peak regions: $k/\beta \approx (1 - 10)$

PT Temperature ~ DM Mass

$$f_{\mathrm{peak}}^{(B)} = 3.33 \times 10^{-8}\ \mathrm{Hz} \times \left(\frac{g_*}{80}\right)^{\frac{1}{6}} \left(\frac{T_*}{1\ \mathrm{GeV}}\right) \left(\frac{\beta}{\mathcal{H}_*}\right)$$

# Experiments




Pulsar timing arrays
Data already available

* From A. Petiteau

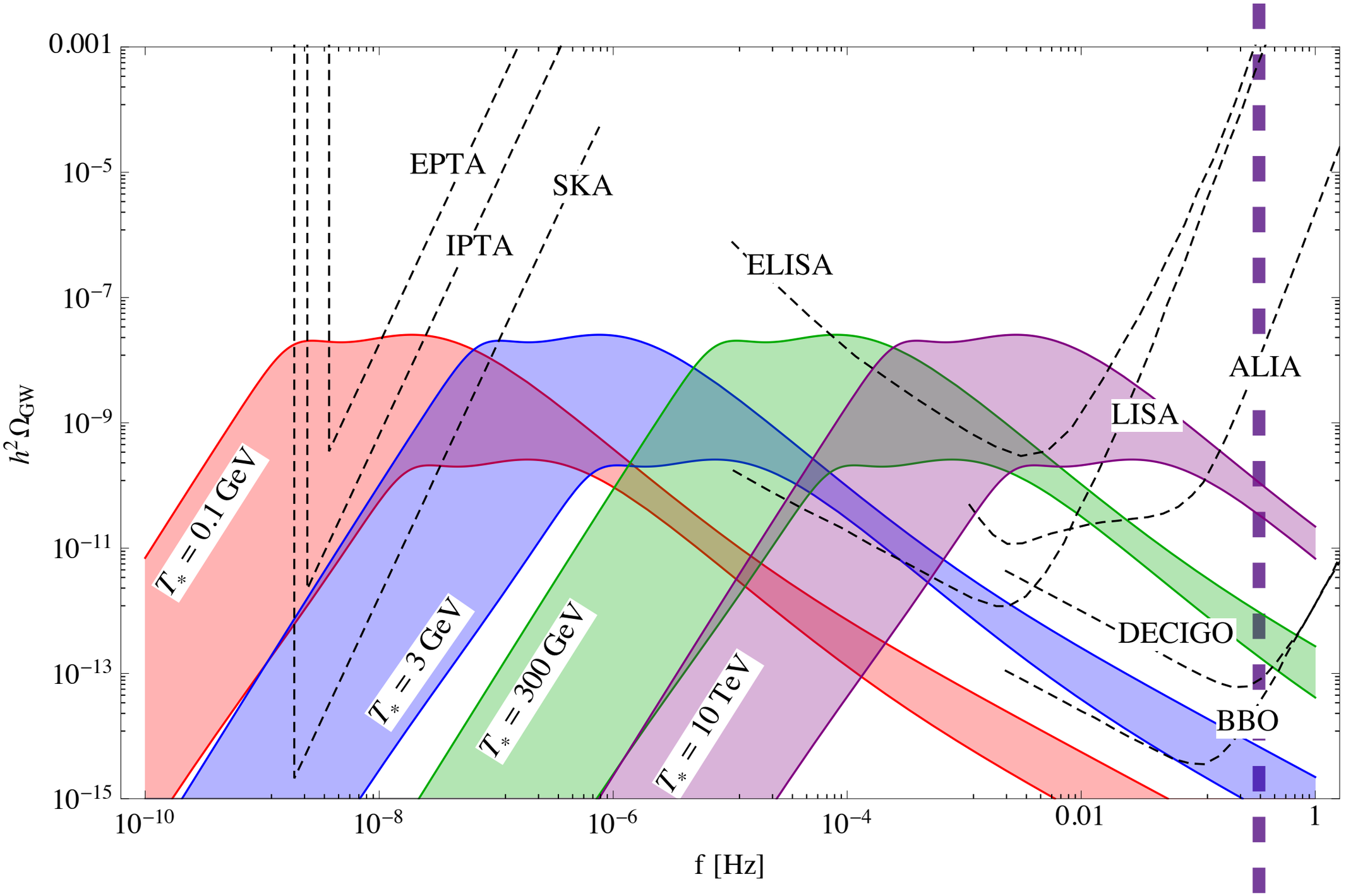
SIMP

Composite ADM Twin Higgs

Composite WIMP-y

DM Unitarity

B-L breaking, Hidden Sectors



# Summary

- Symmetry breaking with first order PT → Gravitational Waves!

- Signal from composite DM sector could be observable

- Interesting tasks for numerical (lattice) simulations
  - PT dynamics for strongly coupled models
  - PT non-perturbative sometimes even for weakly coupled models
  - Simulation of GW signal from PT

# GWs as window to dark matter sector

- Motivation for (non-abelian) Dark Sectors

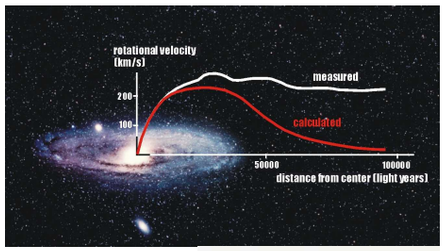
- Phase Transition of SU(N) Theories

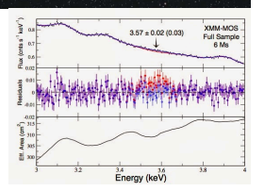
- GW Signals from PTRs to ELISA

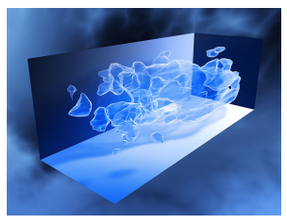
Based on PRL 115 (2015) 18, 181101

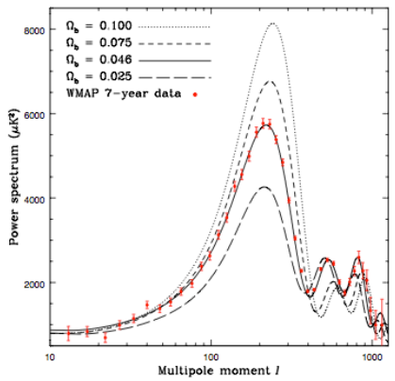
# Dark Matter

We have seen DM in the sky:

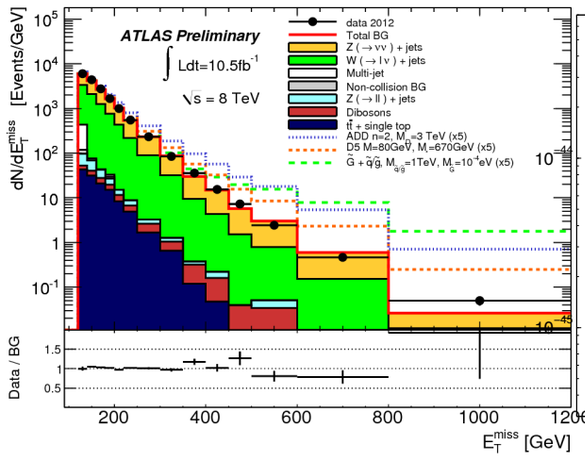


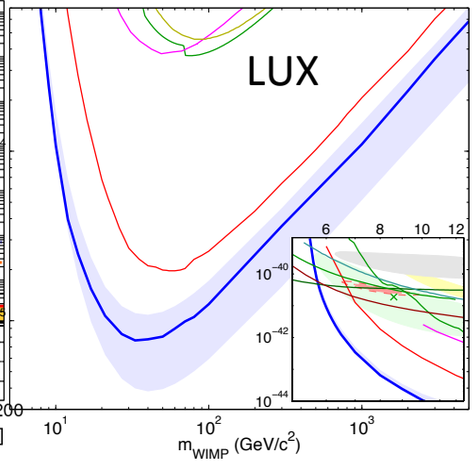






But no direct observation

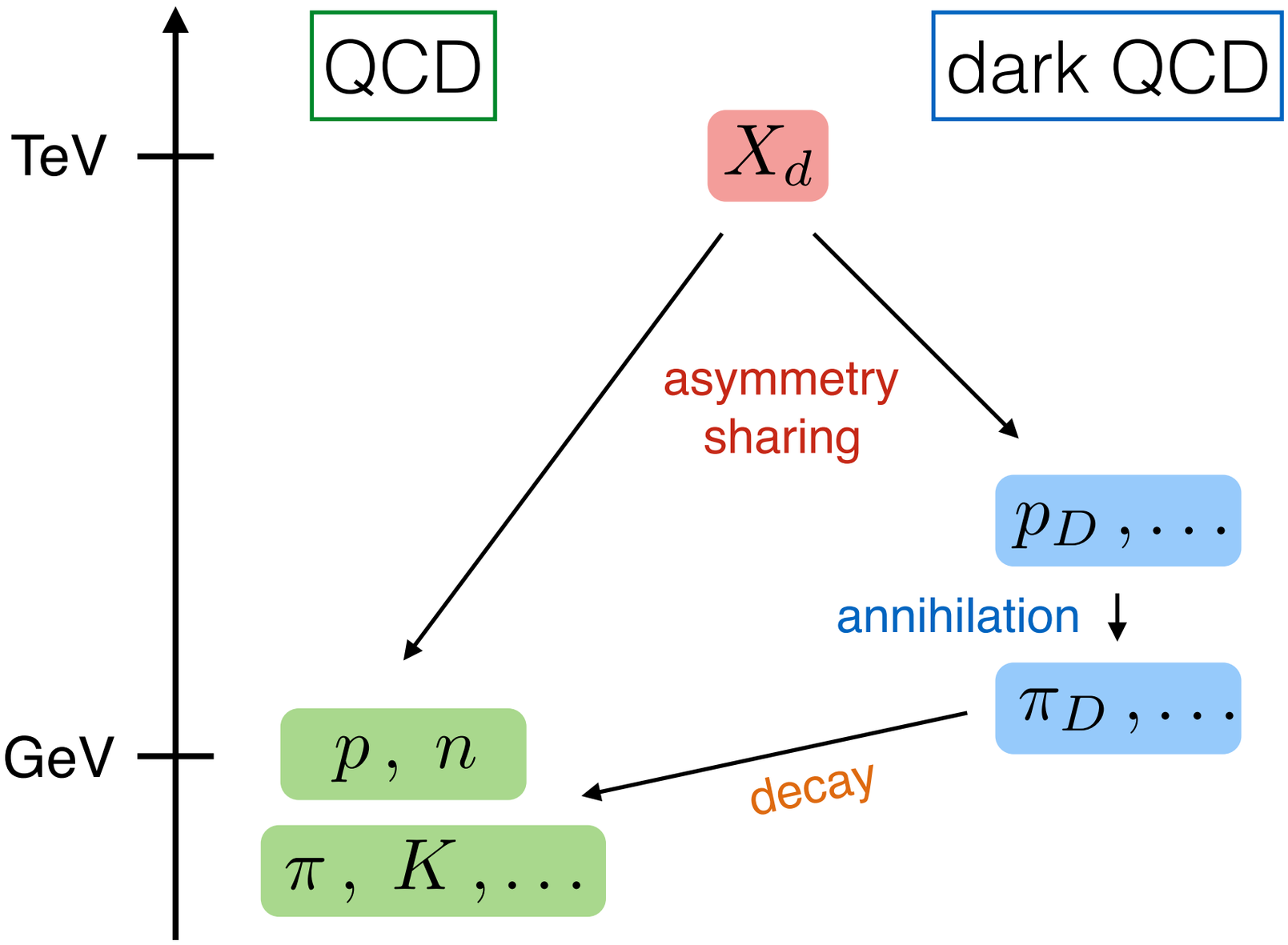



Maybe DM is just part of a larger dark sector

- Example: Proton is massive, stable, composite state
- DM self interactions solve structure formation problems
- New signals, new search strategies!

# Composite DM




- SU(N) dark sector with neutral "dark quarks"
- Confinement scale $\Lambda_{\rm darkQCD}$
- DM is composite "dark proton"

Bai, PS, PRD 89, 2014
PS, Stolarski, Weiler, JHEP 2015

many other works!
Similar setup e.g.: Blennow et al; Cohen et al; Frandsen et al;
Reviews: Petraki & Volkas, 2013; Zurek, 2013;

# DM Motivation

- New mechanisms for relic density, extend mass range:
  - Asymmetric DM - GeV-TeV scale
  - Strong Annihilation - 100 TeV scale
  - SIMP - MeV scale
    Hochberg, Kuflik, Volansky, Wacker, 2014; + Murayama, 2015
- Advantages of Composite
  - DM mass scale and stability
  - Fast annihilation for ADM
  - Self-interactions for structure formation

# GW spectra

- Lot of work on GW from 1st order PT
  - Still difficult to simulate or model

See talks by Hindmarsh, Weir for more details

- Here in addition:
  - Transition is non-perturbative
  - Parameters not known - take an optimistic guess

$$\beta/H_* = 1 - 100$$

$$v = 1$$

$$\frac{\kappa\alpha}{1+\alpha} = 0.1$$